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Direct Radiation Measurements for the Evaluation of Process Heat Systems with Concentrating Solar Thermal Collectors

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Abstract

For the evaluation of the performance of thermal and photovoltaic concentrating solar systems a detailed determination and measurement of the Direct Normal Irradiance (DNI) is essential. The most accurate way of measuring this is with a bi-axial tracking pyrheliometer. However due to its high investment cost and need of maintenance, cost-efficient alternatives are of interest, especially for monitoring projects. This work presents an investigation of the performance and reliability of different alternative devices for the determination of the DNI, which are a sunshine pyranometer SPN1 device and a Rotating Shadowband Irradiometer (RSI). While the pyrheliometer directly measures the DNI via 2-axis tracking, the SPN1 and RSI determine the DNI through the measurement of the global and the diffuse irradiation and the information of the location and solar time. In order to investigate the suitability and reliability of these alternative instruments we have recorded data of about two years in 10 s resolution for the pyranometer SPN1 and pyrheliometer and of about 1 year in 1-minute resolution for the RSI and analyzed the data up to an irradiance of 950W/m^2.

Keywords: *Direct Normal Irradiance measurements, Pyrheliometer, Sunshine Pyranometer SPN1, Rotating Shadowband Irradiometer RSI*

1. Introduction

Accurate and reliable solar irradiance measurements of the global horizontal irradiance (GHI) and its fractions, such as the direct normal irradiance (DNI) and the diffuse horizontal irradiance (DHI), play an important role for solar resource assessments, either for short–term forecasting or for monitoring of solar plants. For solar power plants with concentrating systems, which can be photovoltaic or thermal collectors, the determination of the DNI is essential to evaluate their performance. Also solar thermal plants, which cover a lower temperature range (<300°C) compared to solar thermal power plants have been gaining a lot of attention for applications in industry and are becoming a promising source for process heat.

With the increasing awareness for the need of a more environmentally friendly and energy efficient industry, in the past few years several plants with solar thermal collectors have been installed in Swiss companies and are being monitored and evaluated by the SPF Institute for Solar Technology. For process temperatures between 100°C and 300°C concentrating collectors (parabolic trough and linear Fresnel collectors) are the most suitable technology and are used in three dairies in Switzerland. In order to evaluate the performance of these fields an accurate measurement of the DNI is essential. The most accurate way to do this is by a bi-axially tracking pyrheliometer. Collector developers and research institutes therefore use this instrument. However, a tracking pyrheliometer requires some maintenance and the costs are relatively high (approximately 15'000 Euros). For monitoring projects with field measurements of systems providing solar process heat such costs are in most cases too high.

In this study, we present our evaluation of two less expensive alternative instruments for the measurement of direct normal irradiation DNI: (1) the "Sunshine Pyranometer" SPN1 and (2) the "Rotating Shadow band

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Irradiometer" RSI in comparison to the bi-axial pyrheliometer for DNI and pyranometers for GHI and DHI measurements. For this, all devices are setup and evaluated at the test facilities at the SPF Institute of Solar technology in Rapperswil. In the case of the above-mentioned solar process heat plants, SPN1 devices are used for the measurement of the DNI. The here presented results are the basis for further studies on how to consider the deviation of the SPN1 or RSI devices to the pyrheliometer in the evaluation of solar plants when using these alternative instruments.

2. Materials and Methods

The evaluation of the radiation meters is carried out using the instruments and test stands at the SPF Institute for Solar Technology in Rapperswil, Switzerland. A bi-axially tracking pyrheliometer is used as the reference instrument for the DNI measurements (figure 1c). In Fig. 1 a (left) the pyranometer and a pyranometer with a shadow-ring are shown, which are used for the reference instrument for the GHI and DHI respectively. All instruments are cleaned daily.

While the pyrheliometer directly measures the DNI via 2-axis tracking and a view-limiting aperture of 5°, the SPN1 and RSI compute the DNI through the measurement of the global and the diffuse irradiation and the information of the location and solar time. In the SPN1 (Fig. 1a (center)) six sensors are placed on a hexagonal shape and one sensor in the center on a horizontal plane behind a complex shading mask. The shape of the shading mask ensures that at least one of the sensors is completely shaded and at least one is fully exposed to the solar irradiation, which allows measuring simultaneously GHI and DHI. The big advantage of the SPN1 is that no moving parts in need of continual accurate alignment are required, decreasing the maintenance cost. In the RSI instrument (Fig. 1b) two Silicon-based semiconductors sensor measure the GHI. Every 30s the shadow band rotates 360° around the sensors, which leads to a momentary shading. During the rotation phase of about 1s duration, data is collected in a frequency of 1kHz from which an internal algorithm computes the DHI after two cycles (about one minute).

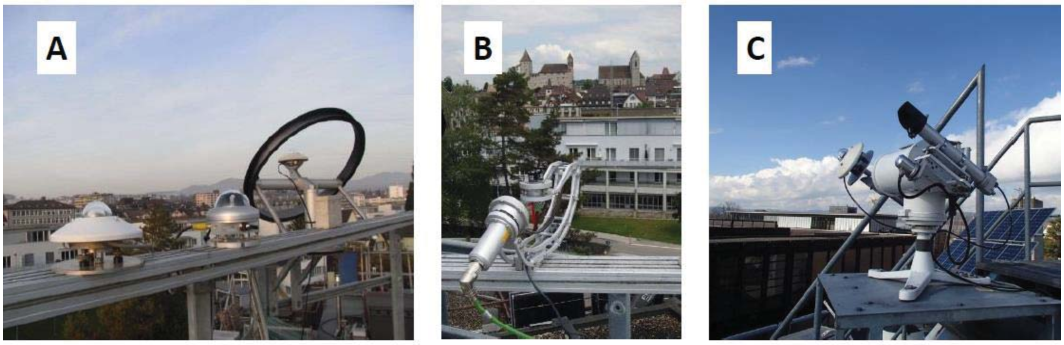

Fig. 1: (A) Pyranometer for the measurement of the horizontal global radiation (left), "Sunshine Prynometer SPN1" (center), pyranometer with shadow-ring for measurement of the horizontal diffuse radiation (right). (B) "Rotating Shadow band Irradiometer RSI". (C) Tracking pyrheliometer for DNI measurements used as reference. All instruments are installed at the SPF Institute for Solar Technology in Rapperswil, Switzerland

We have recorded data of about one year (8.8.2015-7.8.2016) in 10 s resolution for the SPN1, the pyranometer and pyrheliometer and in 1-minute resolution for the RSI and analyzed the data up to an irradiance of 950W/m^2. Data that showed obvious discrepancy due to operation failure was removed from the study. All data was evaluated using the recommended quality control test (Roesch et al., 2011)

The DNI value is calculated via

$$DNI = \frac{GHI - DHI}{\sin(\gamma_s)} \qquad \text{(eq. 1)}$$

where γ_s represents the elevation angle of the sun.

The evaluation of the measurements relative to the reference instruments and the quantitative criteria to describe the absolute and relative dispersion was done based on the publication of Badossa (2014). The slope of the data was determined by a linear regression forced to zero. The standard deviation around the fitting line was calculated as follows:

$$STDE = \sqrt{\frac{\sum_{t=1}^{N}(I_{SPN1/RSI} - I_{ref} \cdot slope)^2}{N}} \qquad \text{(eq. 2)}$$

I stands for DHI, GHI or DNI. The index indicates the measuring device SPN1, RSI or by any of the reference instruments. N is the total number of values. The regression coefficient R^2 is calculated via:

$$R^2 = 1 - \frac{\sum_{t=1}^{N}(I_{SPN1/RSI} - I_{ref} \cdot slope)^2}{\sum_{t=1}^{N}(I_{SPN1/RSI} - \bar{I}_{SPN1/RSI})^2} \qquad \text{(eq. 3)}$$

$\bar{I}_{SPN1/RSI}$ Indicates the average value. Coefficient values larger than 0.99 indicate a high correlation.

3. Results for RSI and SPN1 vs Pyrheliometer and Pyranometer

In the following figures the deviation between the measurement values for DNI, GHI and DHI for the reference methods (pyrheliometer, pyranometer) and the alternative detectors SPN1 and RSI are shown.
An overview of all irradiance measurements during a day with clear sky conditions for all measuring methods is shown in **Error! Reference source not found.**. It can be seen, that the RSI measures lower values for DHI and DNI, while the SPN1 overlaps well with the reference measurements. The DNI line for the SPN1 shows a step around noon. This was observed for several days. One possible explanation is a mismatch of the different detectors with the SPN1 device or to dome lensing (Badossa (2014)). Further investigations are planned in order to resolve this issue.

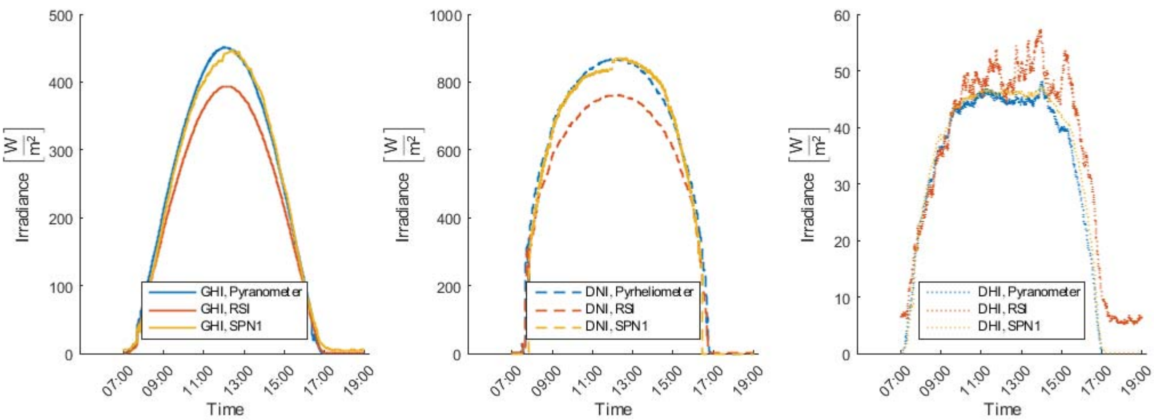

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Fig. 2 Overview of GHI, DHI and DNI measurements with SPN1 and RSI and reference devices for one day with clear sky conditions at Rapperswil, Switzerland

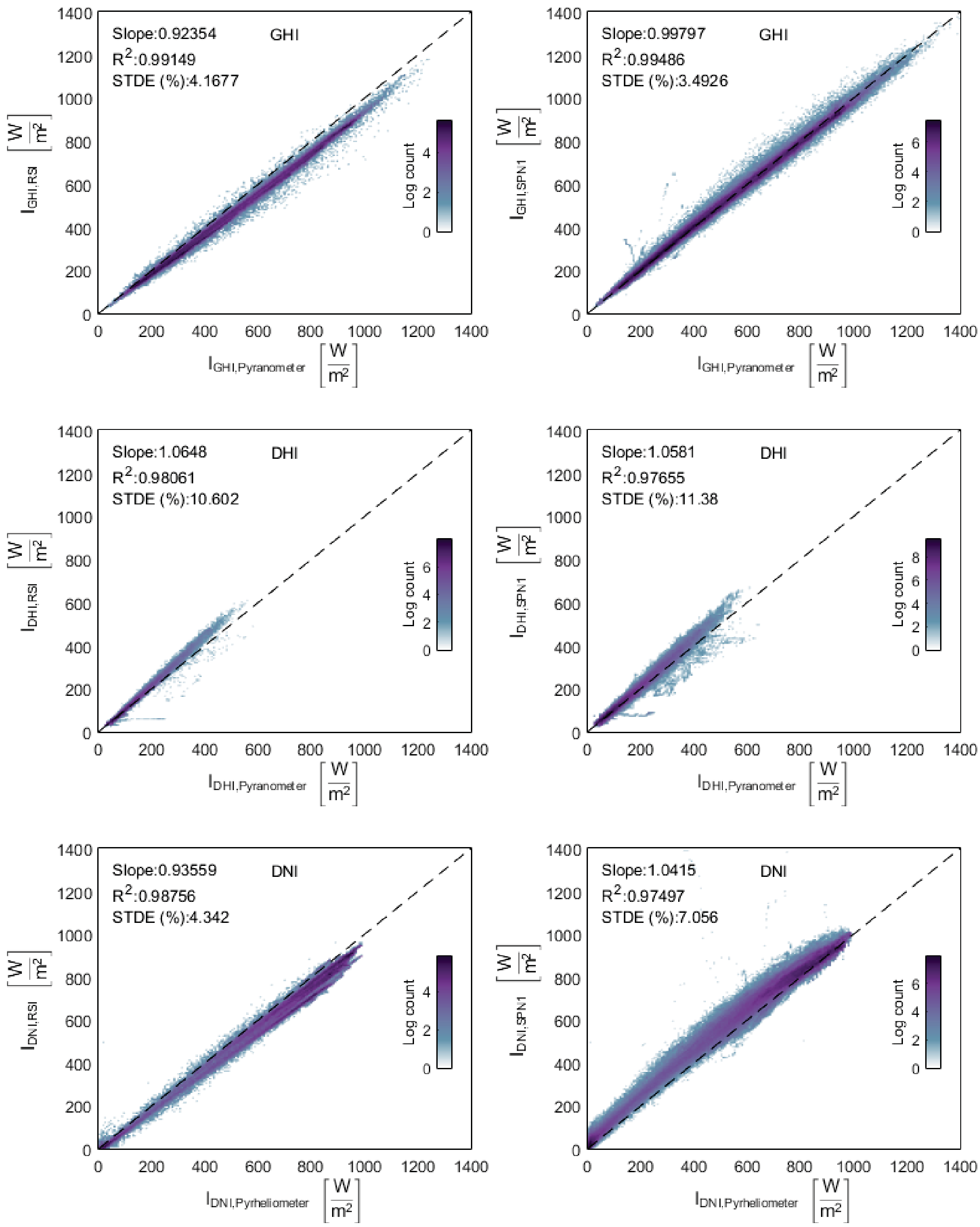

Fig. 3: Scatter plots of GHI, DHI and DNI for SPN1 and RSI in comparison to the pyranometer, pyranometer with shadow-ring and bi-axial tracking pyrheliometer, respectively. Measurements were performed at Rapperswil, Switzerland.

The scatter plots in Fig. 3 show the comparison between SPN1 or RSI vs the reference instruments, the pyrheliometer for the DNI and the pyranometers with and without shadow ring for the DHI and GHI measurements. The slope values indicated in each graph are obtained via a linear regression. The scatter plots show for both, SPN1 and RSI, the smallest spread of data points for the GHI and the largest spread (STDE 4.2% and 3.5%) for the DHI (STDE 10.6% and 11.4%). Furthermore, we see that the data spread becomes narrower for values above 800W/m^2. The slope values reflect well the previous observation done for **Error! Reference source not found.**. The slope value of 0.92 for the RSI measurement indicate an underestimation for GHI. While the slope of 0.998 confirms the good agreement between the GHI measured by the SPN1 and the pyranometer. For the DHI comparison, both devices overestimate the values as indicated by the slope of 1.06. The SPN1 overestimates the DNI value, as indicated with the slope of 1.04. The RSI instrument underestimates the DNI value with a slope of 0.93. Furthermore, we observe for the RSI DNI several lines. Since those lines are not visible in the DHI and GHI measurements, we assume that they are an artifact caused by the internal algorithm that is used to determine the DNI.

In the following, we will focus on the relative deviation for the DNI between the values of the reference pyrheliometer and the SPN1 and RSI devices, since these values are the most important for the evaluation of the performance of concentrating collectors.

DNI : RSI vs Pyrheliometer

Fig. 4 shows the relative deviation for the RSI from the values measured by the pyrheliometer. The data shows a broad spread of data points for low irradiance values, due to the division by values near to zero at low sun elevation angles (eq. 1). For the evaluation of concentrating collectors the more interesting range of irradiance is above 600W/m^2, where the spread is also narrower and the maximal deviation is around 15%. For a better visualization, the histograms in Fig. 5 show the distribution for different irradiance values: (400 ±25)W/m^2, (600 ±25)W/m^2 and (800 ±25)W/m^2. For all three graphs we observe a negative deviation, which shows the underestimation of the DNI. Furthermore, two clusters at -5% and -12% are clearly visible. In Fig. 6 the relative deviation for the RSI from the values measured by the pyrheliometer for a restricted irradiance range between 700 W/m^2 to 900W/m^2 is shown. In addition, the data points are associated with the seasons. From this representation we discover clear lines for each season. Based on this, we can assign the two clusters observed in the histograms to the seasons. The lower deviation corresponds to summer and spring, while the higher deviation value can be attributed to winter and autumn. This is an indication of the dependency of the measurements and the solar altitude.

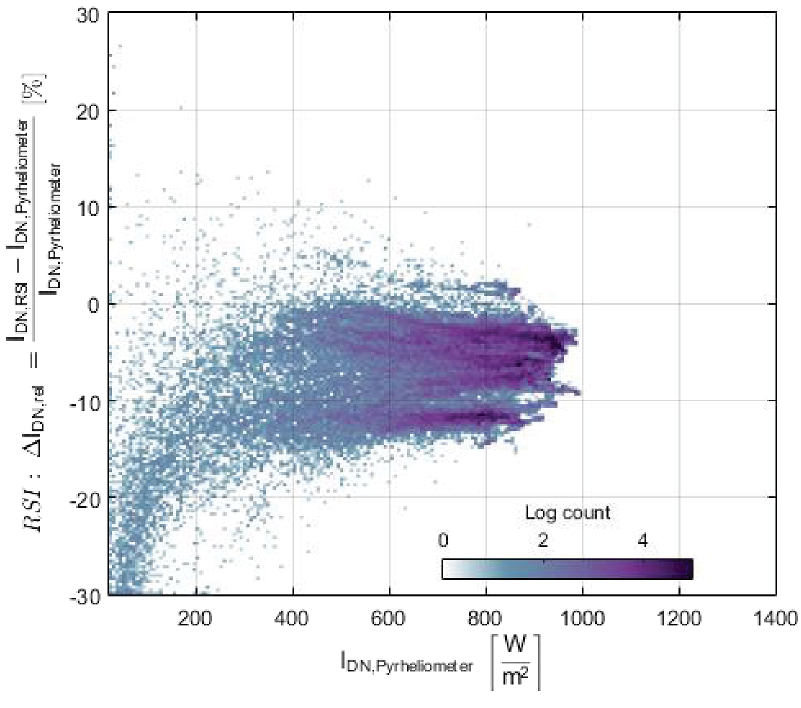

Fig. 4: Relative deviation of the calculated DNI for the RSI vs the values measured by the pyrheliometer.

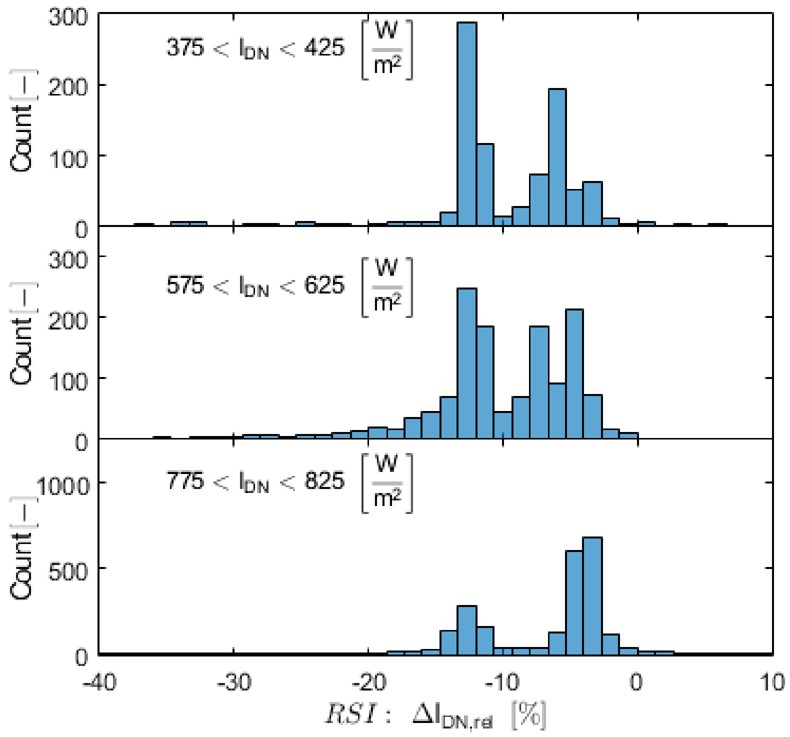

Fig. 5 Histogram indicates the distribution for the relative deviation of the calculated DNI for the RSI vs the values measured by the pyrheliometer at different irradiance values measured (400 ±25)W/m², (600 ±25)W/m² and (800 ±25)W/m².

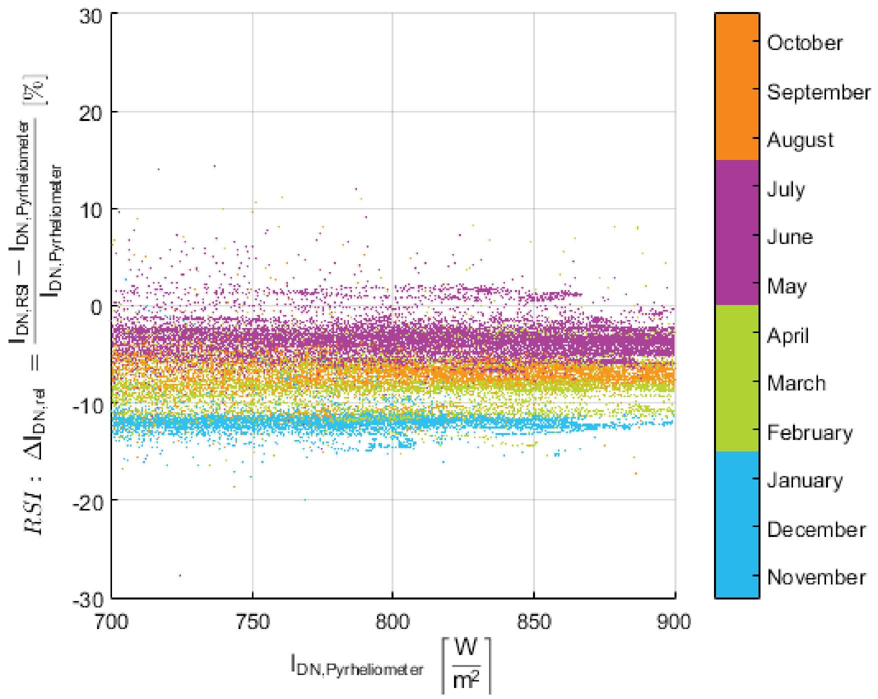

Fig. 6: Zoom of figure 4. Relative deviation of the calculated DNI for the RSI vs the values measured by the pyrheliometer. Color code indicates the seasonal correspondence of each data point.

DNI : SPN1 vs Pyrheliometer

Fig. 7 shows the relative deviation for the SPN1 from the values measured by the pyrheliometer. Similar to the data for the RSI in figure 4, the data shows a broad spread of data points for low irradiance values, due to the division by values near to zero at low sun elevation angles (eq.1). The positive deviation indicates an overestimation of the SPN1 in comparison to the pyrheliometer. The histograms in Fig. 8 show the spread of the data points at different irradiance values: (400 ±25)W/m^2, (600 ±25)W/m^2 and (800 ±25)W/m^2. In contrast to the RSI data, the data for the SPN1 show a more symmetric Gaussian shaped distribution around one center value, which moves closer to zero with increasing irradiance value. For (400 ±25)W/m^2 the mean value is at 16% , at (600 ±25)W/m^2 it is about 9% and for (800 ±25)W/m^2 it is around 3%. The variance μ and the STDE of the distribution also decreases with increasing irradiance values. The representation of the deviation in correspondence of the seasons (Fig. 6) shows no striking seasonal dependency, as could be observed for the RSI measurements in Fig. 9. Only for values lower than 800W/m^2 there is a slight difference visible between summer and winter months.

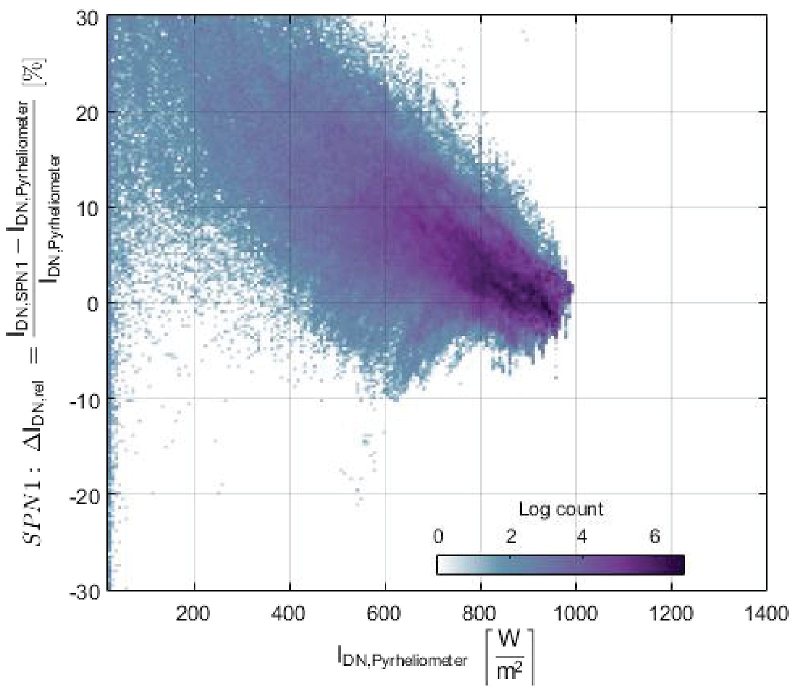

Fig. 7: Relative deviation of the calculated DNI for the SPN1 vs the values measured by the pyrheliometer.

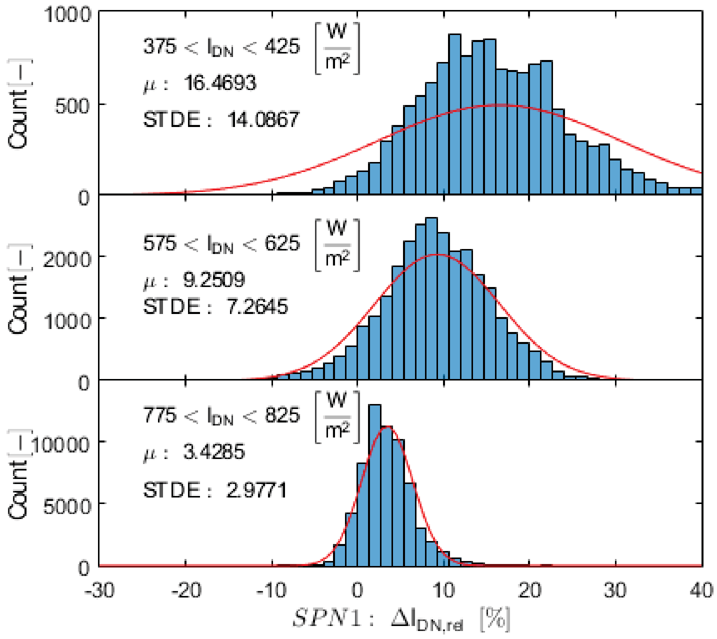

Fig. 8 The histograms indicate the distribution for the relative deviation of the calculated DNI for the SPN1 vs the values measur by the pyrheliometer at different irradiance values measured (400 ±25)W/m^2, (600 ±25)W/m^2 and (800 ±25)W/m^2.

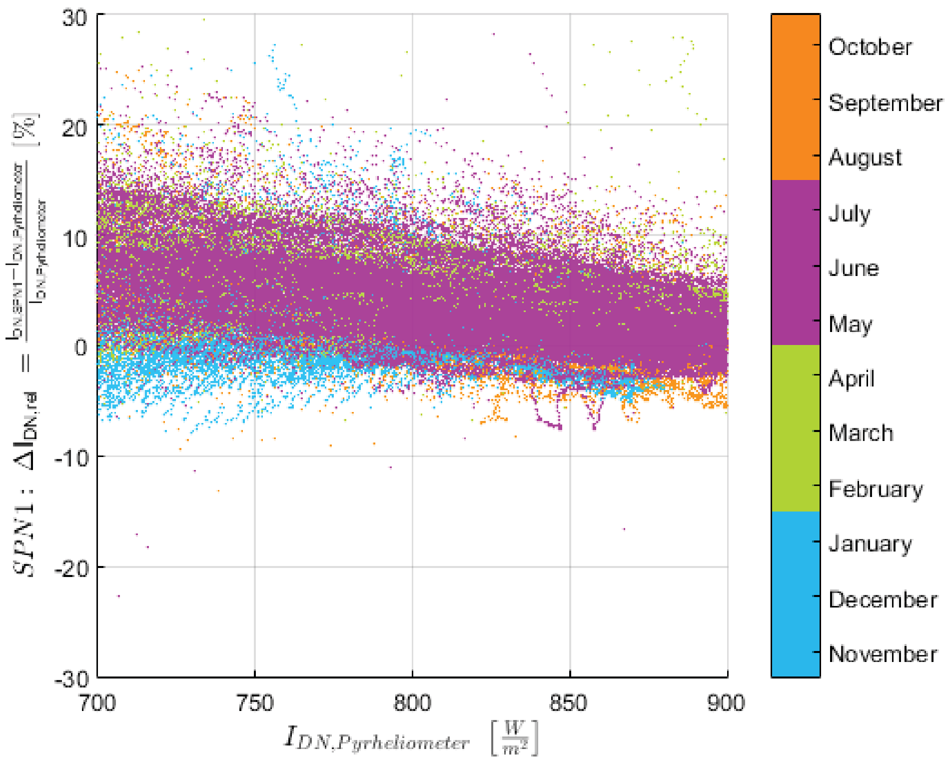

Fig. 9: Zoom of figure 7. Relative deviation of the calculated DNI for the SPN1 vs the values measured by the pyrheliometer. Color code indicates the seasonal correspondence of each data point.

4. Conclusion and Discussion

When comparing the RSI and the SPN1 it can be stated that the data for the RSI is less spread and shows the tendency to underestimate the DNI. The measurement for the SPN1 show a wider spread and indicate a slight overestimation of the DNI. The slope value for the SPN1 is in agreement with values obtained by Badosa et al. (2014), who determined a slope of 1.05 for Payerne, a location with similar conditions as Rapperswil. Both, the SPN1 and RSI device show a broad data spread for lower irradiance values below 400 W/m^2. The data shows a strong increase of the deviation for data points with very low irradiance values, due to the division by values near to zero at low sun elevation angles (eq.1). However, for the range above $600W/m^2$, which is more relevant for concentrating collectors, the spread becomes narrower. The overestimation of the DNI by the SPN1 can be explained by the inclusion of a larger part of the circumsolar aureole at certain solar angles in comparison to the pyrheliometer, which has a limiting opening aperture (Badosa (2014)). For the SPN1 the results indicate a mean deviation of about 9% from the Pyrheliometer at $600W/m^2$, which is in good agreement with previous studies (Badossa et al. (2014), D.R. Myers(2010), Rommel and Larcher (2015) and Rommel et al. (2016)). In addition, it only shows a deviation of 3.4% at an irradiance of $800W/m^2$. For the RSI the deviation varies depending on the season, for summer 5% and 15% for winter season depending on the altitude of the sun.

We conclude that both alternative devices, SPN1 and RSI, show reliable measurements of the DNI at ranges above $600W/m^2$ and are suitable for field monitoring of solar plants with concentrating collectors. These results are the basis for further investigations and detailed analysis of the accuracy and handling characteristics of these alternative devices with the aim to propose how to incorporate our findings into the evaluation of the performance of solar fields with concentrating collectors.

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